



TECHNICAL NOTE

D-299

EFFECT ON GASEOUS FILM COOLING OF COOLANT INJECTION
THROUGH ANGLED SLOTS AND NORMAL HOLES

By S. Stephen Papell

Lewis Research Center
Cleveland, Ohio

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SUMMARY

A study was made to determine the effect of coolant injection angularity on gaseous film-cooling effectiveness. In the correlation of experimental data an effective injection angle was defined by a vector summation of the coolant and mainstream gas flows. The cosine of this angle was used as a parameter to empirically develop a corrective term to qualify a correlating equation presented in Technical Note D-130 that was limited to tangential injection of the coolant.

Data were also obtained for coolant injection through rows of holes normal to the test plate. The slot correlating equation was adapted to fit these data by the definition of an effective slot height. An additional corrective term was then determined to correlate these data.

INTRODUCTION

As part of a basic investigation carried out at the NASA Lewis Research Center for determining the characteristics and possible usefulness of the gaseous film cooling (refs. 1 and 2), a study was made to determine the effect of coolant injection angularity on film-cooling effectiveness. This information is necessary for the application of gaseous film cooling because design criteria often dictate the angle at which the coolant can be applied to protect a surface heated by a hot gas stream.

Intuitively it can be reasoned that increased fluid mixing caused by any initial angularity between the two gas streams should result in decreased film-cooling effectiveness. This fact was illustrated in reference 3, which showed up to a 50-percent reduction in effectiveness caused by normal injection of the coolant as compared to tangential. A gaseous film-cooling correlating equation has been presented in reference 2, which was based on a simplified theoretical heat-transfer model and qualified by empirically determined constants and parameters. Although this equation was developed by using data covering a wide range of coolant gas

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properties and values of basic parameters, it was, however, limited to tangential injection of the coolant parallel to an adiabatic wall. It was the purpose of the present investigation to determine the effect that nontangential injection of the coolant would have on film-cooling effectiveness.

Data were obtained for coolant injection through slots at angles up to and including 90° relative to the adiabatic wall and also through series of normal holes. These data were restricted to the case of subsonic flow with no pressure gradient in the flow direction. Correction terms for the correlation of reference 2 were obtained to account for injection angle and for injection through normal holes.

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APPARATUS AND TEST CONFIGURATIONS

The film-cooling facility and test procedure described in reference 1 were used to obtain the present angle effect data. The test plate was the insulated top wall of an 8- by 8-inch duct 36 inches in length. Figure 1(a) is a schematic representation of the reference 1 slot configuration adapted to hold a series of 3/8-inch-thick plates in which slots were cut at angles of 30° , 60° , and 90° . The slots were approximately 7 inches wide and were installed in the test section so that the injection angles were measured relative to the adiabatic wall. The slot heights were standardized at 1/4 inch measured normally to the guiding walls.

Inasmuch as the ratio of slot guiding wall length in the direction of coolant flow to the 1/4-inch slot height was small, a check was made to determine the actual angle at which the coolant discharged relative to the flat plate. Water injection was used to simulate coolant flow by discharging the fluid through the slots to ambient conditions. The three slot configurations were found to discharge the fluid at angles of 45° , 80° , and 90° . Hereinafter these angles will be referred to as the coolant injection angles (i).

Data were also obtained using two coolant injection configurations illustrated schematically in figure 1(b). They consisted of two and four rows of 1/4-inch holes discharging normally to the test plate. The holes were set in rows on 1/2-inch centers with each succeeding row staggered so as to form a continuous flow area.

The film-cooled adiabatic wall was exposed to a 1500° R main gas stream. For a given mainstream Mach number a range of coolant flow rates was investigated. The following table lists configurations run, test conditions, and range of variables:

	Slot configurations			Hole configurations	
				Four rows of 1/4-in. holes	Two rows of 1/4-in. holes
Injection angle	90°	80°	45°	90°	90°
Main- stream Mach number	0.2; 0.5; 0.7	0.5	0.5	0.3; 0.6; 0.7	0.7
$\frac{V_g}{V_c}$ range	0.53 to 17.47	0.75 to 8.38	0.76 to 9.05	0.49 to 21.83	0.90 to 12.80

CORRELATING PROCEDURE

Preliminary plots of the present data, of which figure 2 is typical, illustrate the loss in film-cooling effectiveness caused by a variation of coolant injection angle from 0° to 90°. The data on this plot were obtained using four different angle configurations, which were run under identical flow conditions and holds for a particular wall position along the test plate. The zero injection angle data were obtained from reference 1. The curves of constant specific weight flow ratio $(\rho V)_c/(\rho V)_g$ show a significant decrease in cooling effectiveness with increasing angle.

In order to postulate a physical system for determining significant parameters that might explain this angle effect, a flow model was set up (fig. 3) which schematically illustrates the action of the main gas stream on the coolant flow. Inasmuch as the coolant is turned in the direction of the mainstream flow, an effective injection angle i_{eff} is defined by the vector sum of the specific weight flows of both streams relative to the test plate. The following equation is a result of this summation:

$$i_{eff} = \tan^{-1} \frac{\sin i}{\cos i + \frac{(\rho V)_g}{(\rho V)_c}} \quad (1)$$

Although several approaches to the problem were attempted, it was found that best results for correlating experimental data were obtained by employing the cosine of this effective angle as a correlating parameter.

By applying the previous analysis to the data presented in table I(a), a corrective term to the reference 2 equation for coolant injection angularity was determined as the \log_e cosine of 0.8 of the effective injection angle.

The resulting correlating equation is:

$$\log_e \eta = - \left\{ \left[\frac{h_g L x}{(\dot{w} c_p)_c} - 0.04 \right] \left(\frac{SV_g}{\alpha_c} \right)^{0.125} f \left(\frac{V_g}{V_c} \right) \right\} + (\log_e \cos 0.8 i_{eff}) \quad (2)$$

The first term of the right side of this equation was taken from reference 2, which holds for tangential injection of the coolant or an effective angle of zero. The second term is the angle correction developed in the present investigation which holds for coolant injection angles up to and including 90° . The various parameters and functions are defined in the appendix.

PRESENTATION AND DISCUSSION OF DATA

Coolant Injection Through Slots at Various Angles

Presentation of correlated data. - Figures 4 to 6 present the data correlation using equation (2) and the slot angle effect data for injection angles of 90° , 80° , and 45° listed in table I(a). The solid line on all figures is the correlating equation. Deviations from this line show the accuracy of the correlation and amount of data scatter. For all test runs the adiabatic wall was exposed to a 1500°R main gas stream. The slot heights of the three angle configurations were standardized at $1/4$ inch measured normally to the guiding walls.

Figures 4(a), (b), and (c) show the results of the data correlation for the 90° coolant injection angle configuration. The main gas stream Mach numbers were set at 0.2, 0.5, and 0.7, respectively. The range of velocity ratios V_g/V_c was obtained by varying the coolant flow rates. In all cases the significant data points are parallel to but below the ideal line. The excessive scatter of the data in figure 4(c) and to a lesser extent in figures 4(a), 4(b), and also latter figures is of little practical interest because it occurs at high-velocity ratios or low values of cooling effectiveness.

A similar data trend is repeated in figure 5, which shows the correlation of data obtained using the 80° injection angle configuration. The 45° angle data correlation presented in figure 6 is somewhat inconsistent in that the data points follow the pattern of the preceding plots only for high values of cooling effectiveness. For values of effectiveness

below approximately 0.7 the data are high. The main gas stream Mach number for both the 80° and 45° injector angle tests was set at 0.5.

Data points consistently falling below the ideal line of figures 4 to 6 can be accounted for as a test facility peculiarity. The main gas flow test section holding the adiabatic plate was approximately an inch wider than the coolant injection slots. Since the slot was centered, the possibility existed for reverse and crossflow of the main gas stream around and above the protecting coolant stream. This addition of heat could then be felt over the length of the test plate. For an annular or continuous slot configuration this effect should be eliminated.

Accuracy of correlation. - Figure 7 is a plot showing the deviation of wall temperature calculated by equation (2) from measured wall temperature for the data presented in figure 4(b). The different symbols in the key are for constant values of velocity ratio.

The scatter of the data points above and below the zero error line is typical of the slot data and shows a maximum error of approximately 10 percent. This value is quite pessimistic since data points of little interest have been included in the plot for high values of velocity ratio and low values of cooling effectiveness. An explanation has also been presented in the data section of this report concerning an error induced by a rig peculiarity that would be eliminated in a practical configuration.

Coolant penalty induced by angle effect. - Figure 8 is presented to illustrate the additional coolant weight penalty induced by an increase of injection angle. The weight flow ratio of coolant injected at some angle to the coolant injected at zero angle is plotted against the effective temperature ratio. The curves of constant injection angle were calculated using equation (2) and are indicative only for the following set of conditions. The mainstream gas temperature and weight flow are 1470°R and 12.0 pounds per second, respectively. The coolant temperature at the slot exit equals 780°R , and the temperature effectiveness holds for a distance of 6.5 inches downstream of the slot. The gas flow passages and cooled area dimensions were taken from the test configuration used to obtain the data presented in figure 4(a) and listed in table I(a).

An examination of figure 8 readily shows that, subject to these conditions, the angle effect is insignificant for low values of cooling effectiveness. At an effectiveness of 0.6 the maximum injection angle requires a coolant weight penalty of only 29 percent. For values of cooling effectiveness above 0.6 the angle effect is small for low injection angles but becomes quite significant as the angle is increased. For example, at a value of effectiveness equal to 0.83 an injection angle of 60° requires an additional coolant weight penalty of 70 percent.

Figure 8 also illustrates the maximum cooling effectiveness that could be obtained with a specific angle configuration. For this axial location the 60° angle curve shows that the maximum cooling effectiveness possible is equal to 0.83. An increase of coolant weight flow beyond this point would only result in a decreased cooling effectiveness.

The explanation of this phenomenon is simply that when the coolant stream has sufficient energy to penetrate deeply into the main gas stream it induces excessive mixing resulting in a reduced cooling effectiveness at the wall. This decrease in film-cooling effectiveness, as a result of an increase in coolant flow, should be noted even though it might only occur beyond coolant weight flows of interest.

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Coolant Injection Through Normal Holes

Data were also obtained using two different hole injection configurations described in the section entitled APPARATUS AND TEST CONFIGURATIONS. Since the correlating equation developed for slot injection of the coolant contains a discrete value of slot height as a basic parameter, it could not be applied directly to the hole configuration data. A modification was made by defining an effective slot height S' as the total coolant flow area divided by the width of the first row of holes (fig. 1(b)):

$$S' = A_c / y \quad (3)$$

Figure 9 shows the results of applying the hole data presented in table I(b) to the slot correlating equation (2), which was modified by equation (3). These data were obtained using the four-row hole configuration having an effective slot height equal to 0.403 inch. The main-stream was held to a Mach number of 0.7 and a temperature of 1500° R. An examination of this plot shows a definite velocity ratio (V_g/V_c) effect which drops the data below the ideal line. It is noteworthy that the data correlate for values of velocity ratio equal to or less than unity.

For values of velocity ratio greater than unity it was found that a corrective term for the modified slot correlating equation equal to $-0.08(V_g/V_c)$ generalizes the data. The resulting correlating equation for normal hole injection of the coolant is:

$$\log_e \eta = - \left[\frac{h_g L x}{(\dot{w}_{c_p})_c} - 0.04 \right] \left(\frac{S' V_g}{\alpha_c} \right)^{0.125} f \left(\frac{V_g}{V_c} \right) + \log_e \cos 0.8 i_{\text{eff}} - 0.08 \left(\frac{V_g}{V_c} \right)_{V_g > V_c} \quad (4)$$

Figure 10 shows the results of applying equation (4) to the data presented in figure 9. The data points now more closely follow the ideal line in the region of interest. The spreading of the coolant stream when discharging through rows of holes may account for the fact that the hole data do not fall below the ideal line as happened on the slot data plots. The same configuration and test conditions were used to obtain the data for figures 11(a) and (b) with the exception of mainstream Mach number, which was set at 0.64 and 0.30, respectively. In both cases the correlation is quite effective.

Figure 12 shows the result of applying equation (4) to data obtained using the two-row hole configuration having an effective slot height of 0.223 inch. The mainstream was set at a Mach number of 0.69 and a temperature of 1500° R. These data also follow the ideal line in the region of interest.

It should be noted that the defining effective slot height equation (3) is strictly empirical, and, as such, it may not be correct to make any generalizations for its use.

CONCLUDING REMARKS

The gaseous film-cooling correlation presented in reference 2 has been extended to cover nontangential coolant injection through slots and two configurations having coolant injection through rows of normal holes.

By use of a simple flow analysis that involved the interaction of the coolant and mainstream gas flows, an effective injection angle was defined by the vector sum of the specific weight flows of both streams relative to the test plate. The cosine of this effective angle was used as a parameter to empirically develop a corrective term for the reference 2 equation. Equation (2) in the body of the report is the slot film-cooling correlating equation that includes the angle correction. Data correlation plots are herein presented for coolant injection angles up to and including 90° measured relative to the test plate.

Data were also obtained for coolant injection through rows of holes normal to the test plate. These data were applied to the slot equation (2) by defining an effective slot height as the total coolant hole flow area divided by the width of the first row of holes. It was found that the hole data correlated for velocity ratios equal to or less than unity. For values of velocity ratio greater than unity a corrective term was

determined empirically. Equation (4) in subject report is the correlating equation that holds for the normal hole coolant injection configurations covered in this investigation.

Lewis Research Center
National Aeronautics and Space Administration
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APPENDIX - SYMBOLS

All parameters in report are dimensionless.

A	gas flow area
c_p	specific heat at constant pressure
D_h	hydraulic diameter
$f\left(\frac{V_g}{V_c}\right)$	$\begin{cases} = 1 + 0.4 \tan^{-1} \left(\frac{V_g}{V_c} - 1 \right) & \text{when } \frac{V_g}{V_c} \geq 1.0 \text{ (angle in radians)} \\ = \left(\frac{V_c}{V_g} \right)^{1.5} [(V_c/V_g) - 1] & \text{when } \frac{V_g}{V_c} \leq 1.0 \end{cases}$
h	convective heat-transfer coefficient, $0.0265 \frac{k_f}{D_h} (Re)_f^{0.8} (Pr)_f^{0.3}$
i	coolant injection angle relative to adiabatic wall
i_{eff}	effective coolant injection angle, $\tan^{-1} \left[\frac{\sin i}{\cos i + \frac{(\rho V)_g}{(\rho V)_c}} \right]$
k	coefficient of thermal conductivity
L	width of adiabatic wall
M	Mach number
Pr	Prandtl number
Re	Reynolds number
S	coolant slot height
S'	effective coolant slot height, A_c/y
T	stagnation temperature
T_{ad}	gas stream adiabatic wall (recovery) temperature, $t_g + (Pr)_g^{1/3} (T_g - t_g)$
t	static temperature

V	velocity
\dot{w}	flow rate
x	distance along adiabatic wall in direction of flow
y	width of first row of holes
α	thermal diffusivity, $k/\rho c_p$
η	cooling effectiveness, $\frac{T_{ad} - t_w}{T_{ad} - t_c}$
μ	coefficient of viscosity
ρ	mass density
$\frac{(\rho V)_c}{(\rho V)_g}$	specific weight flow ratio

Subscripts:

c	coolant slot exit
$calc$	calculated
f	properties evaluated at $\frac{t_g + t_c}{2}$
g	main body of gas
m	measured
w	wall

REFERENCES

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3. Seban, R. A., Chan, H. W., and Scesa, S.: Heat Transfer to a Turbulent Boundary Layer Downstream of an Injection Slot. Paper No. 57-A-36, ASME, 1957.

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TABLE I. - COOLANT INJECTION DATA

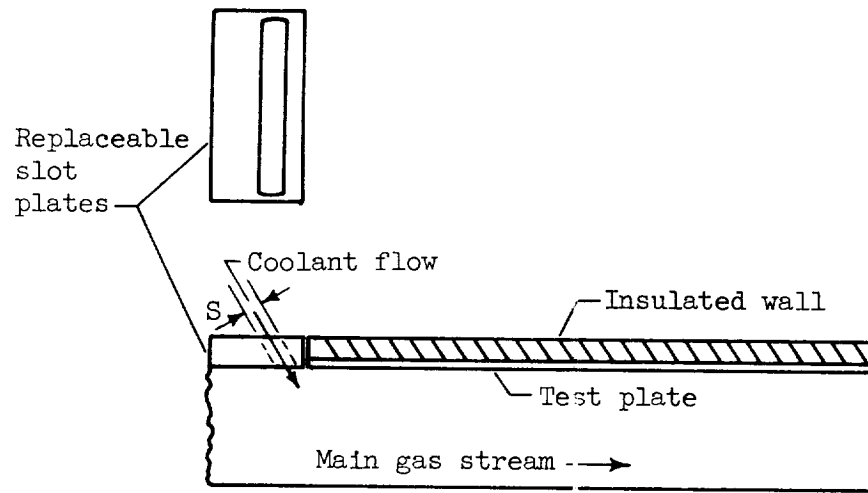
(a) Slots at various angles

Case	L	B	A ₁	A ₂	C ₁	K ₁	A ₁ (Index)	A ₂ (Index)	C ₁ (Index)	C ₂ (Index)	V ₁ (%)	V ₂ (%)	V ₃ (%)	V ₄ (%)	V ₅ (%)	2nd Impedance										At Station		K ₂ (%)	K ₃ (%)	K ₄ (%)	K ₅ (%)	K ₆ (%)	K ₇ (%)	K ₈ (%)	K ₉ (%)	K ₁₀ (%)	K ₁₁ (%)	K ₁₂ (%)	K ₁₃ (%)	K ₁₄ (%)	K ₁₅ (%)	K ₁₆ (%)	K ₁₇ (%)	K ₁₈ (%)	K ₁₉ (%)	K ₂₀ (%)	K ₂₁ (%)	K ₂₂ (%)	K ₂₃ (%)	K ₂₄ (%)	K ₂₅ (%)	K ₂₆ (%)	K ₂₇ (%)	K ₂₈ (%)	K ₂₉ (%)	K ₃₀ (%)	K ₃₁ (%)	K ₃₂ (%)	K ₃₃ (%)	K ₃₄ (%)	K ₃₅ (%)	K ₃₆ (%)	K ₃₇ (%)	K ₃₈ (%)	K ₃₉ (%)	K ₄₀ (%)	K ₄₁ (%)	K ₄₂ (%)	K ₄₃ (%)	K ₄₄ (%)	K ₄₅ (%)	K ₄₆ (%)	K ₄₇ (%)	K ₄₈ (%)	K ₄₉ (%)	K ₅₀ (%)	K ₅₁ (%)	K ₅₂ (%)	K ₅₃ (%)	K ₅₄ (%)	K ₅₅ (%)	K ₅₆ (%)	K ₅₇ (%)	K ₅₈ (%)	K ₅₉ (%)	K ₆₀ (%)	K ₆₁ (%)	K ₆₂ (%)	K ₆₃ (%)	K ₆₄ (%)	K ₆₅ (%)	K ₆₆ (%)	K ₆₇ (%)	K ₆₈ (%)	K ₆₉ (%)	K ₇₀ (%)	K ₇₁ (%)	K ₇₂ (%)	K ₇₃ (%)	K ₇₄ (%)	K ₇₅ (%)	K ₇₆ (%)	K ₇₇ (%)	K ₇₈ (%)	K ₇₉ (%)	K ₈₀ (%)	K ₈₁ (%)	K ₈₂ (%)	K ₈₃ (%)	K ₈₄ (%)	K ₈₅ (%)	K ₈₆ (%)	K ₈₇ (%)	K ₈₈ (%)	K ₈₉ (%)	K ₉₀ (%)	K ₉₁ (%)	K ₉₂ (%)	K ₉₃ (%)	K ₉₄ (%)	K ₉₅ (%)	K ₉₆ (%)	K ₉₇ 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(%)	K ₂₉₈ (%)	K ₂₉₉ (%)	K ₃₀₀ (%)	K ₃₀₁ (%)	K ₃₀₂ (%)	K ₃₀₃ (%)	K ₃₀₄ (%)	K ₃₀₅ (%)	K ₃₀₆ (%)	K ₃₀₇ (%)	K ₃₀₈ (%)	K ₃₀₉ (%)	K ₃₁₀ (%)	K ₃₁₁ (%)	K ₃₁₂ (%)	K ₃₁₃ (%)	K ₃₁₄ (%)	K ₃₁₅ (%)	K ₃₁₆ (%)	K ₃₁₇ (%)	K ₃₁₈ (%)	K ₃₁₉ (%)	K ₃₂₀ (%)	K ₃₂₁ (%)	K ₃₂₂ (%)	K ₃₂₃ (%)	K ₃₂₄ (%)	K ₃₂₅ (%)	K ₃₂₆ (%)	K ₃₂₇ (%)	K ₃₂₈ (%)	K ₃₂₉ (%)	K ₃₃₀ (%)	K ₃₃₁ (%)	K ₃₃₂ (%)	K ₃₃₃ (%)	K ₃₃₄ (%)	K ₃₃₅ (%)	K ₃₃₆ (%)	K ₃₃₇ (%)	K ₃₃₈ (%)	K ₃₃₉ (%)	K ₃₄₀ (%)	K ₃₄₁ (%)	K ₃₄₂ (%)	K ₃₄₃ (%)	K ₃₄₄ (%)	K ₃₄₅ (%)	K ₃₄₆ (%)	K ₃₄₇ (%)	K ₃₄₈ (%)	K ₃₄₉ (%)	K ₃₅₀ (%)	K ₃₅₁ (%)	K ₃₅₂ (%)	K ₃₅₃ (%)	K ₃₅₄ (%)	K ₃₅₅ (%)	K ₃₅₆ (%)	K ₃₅₇ (%)	K ₃₅₈ (%)	K ₃₅₉ (%)	K ₃₆₀ (%)	K ₃₆₁ (%)	K ₃₆₂ (%)	K ₃₆₃ (%)	K ₃₆₄ (%)	K ₃₆₅ (%)	K ₃₆₆ (%)	K ₃₆₇ (%)	K ₃₆₈ (%)	K ₃₆₉ (%)	K ₃₇₀ (%)	K ₃₇₁ (%)	K ₃₇₂ (%)	K ₃₇₃ (%)	K ₃₇₄ (%)	K ₃₇₅ (%)	K ₃₇₆ (%)	K ₃₇₇ (%)	K ₃₇₈ (%)	K ₃₇₉ (%)	K ₃₈₀ (%)	K ₃₈₁ (%)	K ₃₈₂ (%)	K ₃₈₃ (%)	K ₃₈₄ (%)	K ₃₈₅ (%)	K ₃₈₆ (%)	K ₃₈₇ (%)	K ₃₈₈ (%)	K ₃₈₉ (%)	K ₃₉₀ (%)	K ₃₉₁ (%)	K ₃₉₂ (%)	K ₃₉₃ (%)	K ₃₉₄ (%)	K ₃₉₅ (%)	K ₃₉₆ (%)	K ₃₉₇ (%)	K ₃₉₈ (%)	K ₃₉₉ (%)	K ₄₀₀ (%)	K ₄₀₁ (%)	K ₄₀₂ (%)	K ₄₀₃ (%)	K ₄₀₄ (%)	K ₄₀₅ (%)	K ₄₀₆ (%)	K ₄₀₇ (%)	K ₄₀₈ (%)	K ₄₀₉ (%)	K ₄₁₀ (%)	K ₄₁₁ (%)	K ₄₁₂ (%)	K ₄₁₃ (%)	K ₄₁₄ (%)	K ₄₁₅ (%)	K ₄₁₆ (%)	K ₄₁₇ (%)	K ₄₁₈ (%)	K ₄₁₉ (%)	K ₄₂₀ (%)	K ₄₂₁ (%)	K ₄₂₂ (%)	K ₄₂₃ (%)	K ₄₂₄ (%)	K ₄₂₅ (%)	K ₄₂₆ (%)	K ₄₂₇ (%)	K ₄₂₈ (%)	K ₄₂₉ (%)	K ₄₃₀ (%)	K ₄₃₁ (%)	K ₄₃₂ (%)	K ₄₃₃ (%)	K ₄₃₄ (%)	K ₄₃₅ (%)	K ₄₃₆ (%)	K ₄₃₇ (%)	K ₄₃₈ (%)	K ₄₃₉ (%)	K ₄₄₀ (%)	K ₄₄₁ (%)	K ₄₄₂ (%)	K ₄₄₃ (%)	K ₄₄₄ (%)	K ₄₄₅ (%)	K ₄₄₆ (%)	K ₄₄₇ (%)	K ₄₄₈ (%)	K ₄₄₉ (%)	K ₄₅₀ (%)	K ₄₅₁ (%)	K ₄₅₂ (%)	K ₄₅₃ (%)	K ₄₅₄ (%)	K ₄₅₅ (%)	K ₄₅₆ (%)	K ₄₅₇ (%)	K ₄₅₈ (%)	K ₄₅₉ (%)	K ₄₆₀ (%)	K ₄₆₁ (%)	K ₄₆₂ (%)	K ₄₆₃ (%)	K ₄₆₄ (%)	K ₄₆₅ (%)	K ₄₆₆ (%)	K ₄₆₇ (%)	K ₄₆₈ (%)	K ₄₆₉ (%)	K ₄₇₀ (%)	K ₄₇₁ (%)	K ₄₇₂ (%)	K ₄₇₃ (%)	K ₄₇₄ (%)	K ₄₇₅ (%)	K ₄₇₆ (%)	K ₄₇₇ (%)	K ₄₇₈ (%)	K ₄₇₉ (%)	K ₄₈₀ (%)	K ₄₈₁ (%)	K ₄₈₂ (%)	K ₄₈₃ (%)	K ₄₈₄ (%)	K ₄₈₅ (%)	K ₄₈₆ (%)	K ₄₈₇ (%)	K ₄₈₈ (%)	K ₄₈₉ (%)	K ₄₉₀ (%)	K ₄₉₁ (%)	K ₄₉₂ (%)	K ₄₉₃ (%)	K ₄₉₄ (%)	K ₄₉₅ (%)	K ₄₉₆ (%)	K ₄₉₇ (%)	K ₄₉₈ (%)	K ₄₉₉ (%)	K ₅₀₀ (%)	K ₅₀₁ (%)	K ₅₀₂ (%)	K ₅₀₃ (%)	K ₅₀₄ (%)	K ₅₀₅ (%)	K ₅₀₆ (%)	K ₅₀₇ (%)	K ₅₀₈ (%)	K ₅₀₉ (%)	K ₅₁₀ (%)	K ₅₁₁ (%)	K ₅₁₂ (%)	K ₅₁₃ (%)	K ₅₁₄ (%)	K ₅₁₅ (%)	K ₅₁₆ (%)	K ₅₁₇ (%)	K ₅₁₈ (%)	K ₅₁₉ (%)	K ₅₂₀ (%)	K ₅₂₁ (%)	K ₅₂₂ (%)	K ₅₂₃ (%)	K ₅₂₄ (%)	K ₅₂₅ (%)	K ₅₂₆ (%)	K ₅₂₇ (%)	K ₅₂₈ (%)	K ₅₂₉ (%)	K ₅₃₀ (%)	K ₅₃₁ (%)	K ₅₃₂ (%)	K ₅₃₃ (%)	K ₅₃₄ (%)	K ₅₃₅ (%)	K ₅₃₆ (%)	K ₅₃₇ (%)	K ₅₃₈ (%)	K ₅₃₉ (%)	K ₅₄₀ (%)	K ₅₄₁ (%)	K ₅₄₂ (%)	K ₅₄₃ (%)	K ₅₄₄ (%)	K ₅₄₅ (%)	K ₅₄₆ (%)	K ₅₄₇ (%)	K ₅₄₈ (%)	K ₅₄₉ (%)	K ₅₅₀ (%)	K ₅₅₁ (%)	K ₅₅₂ (%)	K ₅₅₃ (%)	K ₅₅₄ (%)	K ₅₅₅ (%)	K ₅₅₆ (%)	K ₅₅₇ (%)	K ₅₅₈ (%)	K ₅₅₉ (%)	K ₅₆₀ (%)	K ₅₆₁ (%)	K ₅₆₂ (%)	K ₅₆₃ (%)	K ₅₆₄ (%)	K ₅₆₅ (%)	K ₅₆₆ (%)	K ₅₆₇ (%)	K ₅₆₈ (%)	K ₅₆₉ (%)	K ₅₇₀ (%)	K ₅₇₁ (%)	K ₅₇₂ (%)	K ₅₇₃ (%)	K ₅₇₄ (%)	K ₅₇₅ (%)	K ₅₇₆ (%)	K ₅₇₇ (%)	K ₅₇₈ (%)	K ₅₇₉ (%)	K ₅₈₀ (%)	K ₅₈₁ (%)	K ₅₈₂ (%)	K ₅₈₃ (%)	K ₅₈₄ (%)	K ₅₈₅ (%)	K ₅₈₆ (%)	K ₅₈₇ (%)	K ₅₈₈ (%)	K ₅₈₉ (%)	K ₅₉₀ (%)	K ₅₉₁ (%)	K ₅₉₂ (%)	K ₅₉₃ (%)	K ₅₉₄ (%)	K ₅₉₅ (%)	K ₅₉₆ (%)	K ₅₉₇ (%)	K ₅₉₈ (%)	K ₅₉₉ (%)	K ₆₀₀ (%)	K ₆₀₁ (%)	K ₆₀₂ (%)	K ₆₀₃ (%)	K ₆₀₄ (%)	K ₆₀₅ (%)	K ₆₀₆ (%)	K ₆₀₇ (%)	K ₆₀₈ (%)	K ₆₀₉ (%)	K ₆₁₀ (%)	K ₆₁₁ (%)	K ₆₁₂ (%)	K ₆₁₃ (%)	K ₆₁₄ (%)	K ₆₁₅ (%)	K ₆₁₆ (%)	K ₆₁₇ (%)	K ₆₁₈ (%)	K ₆₁₉ (%)	K ₆₂₀ (%)	K ₆₂₁ (%)	K ₆₂₂ (%)	K ₆₂₃ (%)	K ₆₂₄ (%)	K ₆₂₅ (%)	K ₆₂₆ (%)	K ₆₂₇ (%)	K ₆₂₈ (%)	K ₆₂₉ (%)	K ₆₃₀ (%)	K ₆₃₁ (%)	K ₆₃₂ (%)	K ₆₃₃ (%)	K ₆₃₄ (%)	K ₆₃₅ (%)	K ₆₃₆ (%)	K ₆₃₇ (%)	K ₆₃₈ (%)	K ₆₃₉ (%)	K ₆₄₀ (%)	K ₆₄₁ (%)	K ₆₄₂ (%)	K ₆₄₃ (%)	K ₆₄₄ (%)
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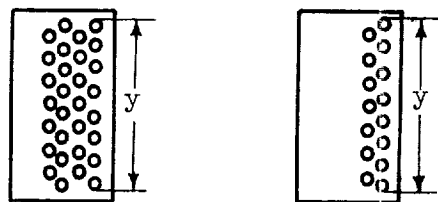
TABLE I. - Concluded. COOLANT INJECTION DATA

(b) Normal holes

Fig- ure	1. in.	2. in.	3. in.	4. in.	5. in.	6. in.	7. in.	8. in.	9. in.	10. in.	11. in.	12. in.	13. in.	14. in.	15. in.	16. in.	17. in.	18. in.	19. in.	20. in.	21. in.	22. in.	23. in.	24. in.	25. in.	26. in.	27. in.	28. in.	29. in.	30. in.	31. in.	32. in.	33. in.	34. in.	35. in.	36. in.	37. in.	38. in.	39. in.	40. in.	41. in.	42. in.	43. in.	44. in.	45. in.	46. in.	47. in.	48. in.	49. in.	50. in.	51. in.	52. in.	53. in.	54. in.	55. in.	56. in.	57. in.	58. in.	59. in.	60. in.	61. in.	62. in.	63. in.	64. in.	65. in.	66. in.	67. in.	68. in.	69. in.	70. in.	71. in.	72. in.	73. in.	74. in.	75. in.	76. in.	77. in.	78. in.	79. in.	80. in.	81. in.	82. in.	83. in.	84. in.	85. in.	86. in.	87. in.	88. in.	89. in.	90. in.	91. in.	92. in.	93. in.	94. in.	95. in.	96. in.	97. in.	98. in.	99. in.	100. in.	101. in.	102. in.	103. in.	104. in.	105. in.	106. in.	107. in.	108. in.	109. in.	110. in.	111. in.	112. in.	113. in.	114. in.	115. in.	116. in.	117. in.	118. in.	119. in.	120. in.	121. in.	122. in.	123. in.	124. in.	125. in.	126. in.	127. in.	128. in.	129. in.	130. in.	131. in.	132. in.	133. in.	134. in.	135. in.	136. in.	137. in.	138. in.	139. in.	140. in.	141. in.	142. in.	143. in.	144. in.	145. in.	146. in.	147. in.	148. in.	149. in.	150. in.	151. in.	152. in.	153. in.	154. in.	155. in.	156. in.	157. in.	158. in.	159. in.	160. in.	161. in.	162. in.	163. in.	164. in.	165. in.	166. in.	167. in.	168. in.	169. in.	170. in.	171. in.	172. in.	173. in.	174. in.	175. in.	176. in.	177. in.	178. in.	179. in.	180. in.	181. in.	182. in.	183. in.	184. in.	185. in.	186. in.	187. in.	188. in.	189. in.	190. in.	191. in.	192. in.	193. in.	194. in.	195. in.	196. in.	197. in.	198. in.	199. in.	200. in.	201. in.	202. in.	203. in.	204. in.	205. in.	206. in.	207. in.	208. in.	209. in.	210. in.	211. in.	212. in.	213. in.	214. in.	215. in.	216. in.	217. in.	218. in.	219. in.	220. in.	221. in.	222. in.	223. in.	224. in.	225. in.	226. in.	227. in.	228. in.	229. in.	230. in.	231. in.	232. in.	233. in.	234. in.	235. in.	236. in.	237. in.	238. in.	239. in.	240. in.	241. in.	242. in.	243. in.	244. in.	245. in.	246. in.	247. in.	248. in.	249. in.	250. in.	251. in.	252. in.	253. in.	254. in.	255. in.	256. in.	257. in.	258. in.	259. in.	260. in.	261. in.	262. in.	263. in.	264. in.	265. in.	266. in.	267. in.	268. in.	269. in.	270. in.	271. in.	272. in.	273. in.	274. in.	275. in.	276. in.	277. in.	278. in.	279. in.	280. in.	281. in.	282. in.	283. in.	284. in.	285. in.	286. in.	287. in.	288. in.	289. in.	290. in.	291. in.	292. in.	293. in.	294. in.	295. in.	296. in.	297. in.	298. in.	299. in.	300. in.	301. in.	302. in.	303. in.	304. in.	305. in.	306. in.	307. in.	308. in.	309. in.	310. in.	311. in.	312. in.	313. in.	314. in.	315. in.	316. in.	317. in.	318. in.	319. in.	320. in.	321. in.	322. in.	323. in.	324. in.	325. in.	326. in.	327. in.	328. in.	329. in.	330. in.	331. in.	332. in.	333. in.	334. in.	335. in.	336. in.	337. in.	338. in.	339. in.	340. in.	341. in.	342. in.	343. in.	344. in.	345. in.	346. in.	347. in.	348. in.	349. in.	350. in.	351. in.	352. in.	353. in.	354. in.	355. in.	356. in.	357. in.	358. in.	359. in.	360. in.	361. in.	362. in.	363. in.	364. in.	365. in.	366. in.	367. in.	368. in.	369. in.	370. in.	371. in.	372. in.	373. in.	374. in.	375. in.	376. in.	377. in.	378. in.	379. in.	380. in.	381. in.	382. in.	383. in.	384. in.	385. in.	386. in.	387. in.	388. in.	389. in.	390. in.	391. in.	392. in.	393. in.	394. in.	395. in.	396. in.	397. in.	398. in.	399. in.	400. in.	401. in.	402. in.	403. in.	404. in.	405. in.	406. in.	407. in.	408. in.	409. in.	410. in.	411. in.	412. in.	413. in.	414. in.	415. in.	416. in.	417. in.	418. in.	419. in.	420. in.	421. in.	422. in.	423. in.	424. in.	425. in.	426. in.	427. in.	428. in.	429. in.	430. in.	431. in.	432. in.	433. in.	434. in.	435. in.	436. in.	437. in.	438. in.	439. in.	440. in.	441. in.	442. in.	443. in.	444. in.	445. in.	446. in.	447. in.	448. in.	449. in.	450. in.	451. in.	452. in.	453. in.	454. in.	455. in.	456. in.	457. in.	458. in.	459. in.	460. in.	461. in.	462. in.	463. in.	464. in.	465. in.	466. in.	467. in.	468. in.	469. in.	470. in.	471. in.	472. in.	473. in.	474. in.	475. in.	476. in.	477. in.	478. in.	479. in.	480. in.	481. in.	482. in.	483. in.	484. in.	485. in.	486. in.	487. in.	488. in.	489. in.	490. in.	491. in.	492. in.	493. in.	494. in.	495. in.	496. in.	497. in.	498. in.	499. in.	500. in.	501. in.	502. in.	503. in.	504. in.	505. in.	506. in.	507. in.	508. in.	509. in.	510. in.	511. in.	512. in.	513. in.	514. in.	515. in.	516. in.	517. in.	518. in.	519. in.	520. in.	521. in.	522. in.	523. in.	524. in.	525. in.	526. in.	527. in.	528. in.	529. in.	530. in.	531. in.	532. in.	533. in.	534. in.	535. in.	536. in.	537. in.	538. in.	539. in.	540. in.	541. in.	542. in.	543. in.	544. in.	545. in.	546. in.	547. in.	548. in.	549. in.	550. in.	551. in.	552. in.	553. in.	554. in.	555. in.	556. in.	557. in.	558. in.	559. in.	560. in.	561. in.	562. in.	563. in.	564. in.	565. in.	566. in.	567. in.	568. in.	569. in.	570. in.	571. in.	572. in.	573. in.	574. in.	575. in.	576. in.	577. in.	578. in.	579. in.	580. in.	581. in.	582. in.	583. in.	584. in.	585. in.	586. in.	587. in.	588. in.	589. in.	590. in.	591. in.	592. in.	593. in.	594. in.	595. in.	596. in.	597. in.	598. in.	599. in.	600. in.	601. in.	602. in.	603. in.	604. in.	605. in.	606. in.	607. in.	608. in.	609. in.	610. in.	611. in.	612. in.	613. in.	614. in.	615. in.	616. in.	617. in.	618. in.	619. in.	620. in.	621. in.	622. in.	623. in.	624. in.	625. in.	626. in.	627. in.	628. in.	629. in.	630. in.	631. in.	632. in.	633. in.	634. in.	635. in.	636. in.	637. in.	638. in.	639. in.	640. in.	641. in.	642. in.	643. in.	644. in.	645. in.	646. in.	647. in.	648. in.	649. in.	650. in.	651. in.	652. in.	653. in.	654. in.	655. in.	656. in.	657. in.	658. in.	659. in.	660. in.	661. in.	662. in.	663. in.	664. in.	665. in.	666. in.	667. in.	668. in.	669. in.	670. in.	671. in.	672. in.	673. in.	674. in.	675. in.	676. in.	677. 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in.	789. in.	790. in.	791. in.	792. in.	793. in.	794. in.	795. in.	796. in.	797. in.	798. in.	799. in.	800. in.	801. in.	802. in.	803. in.	804. in.	805. in.	806. in.	807. in.	808. in.	809. in.	810. in.	811. in.	812. in.	813. in.	814. in.	815. in.	816. in.	817. in.	818. in.	819. in.	820. in.	821. in.	822. in.	823. in.	824. in.	825. in.	826. in.	827. in.	828. in.	829. in.	830. in.	831. in.	832.<
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(a) Slot angle configuration.



(b) Normal hole injection plates.

Figure 1. - Coolant injection configurations.

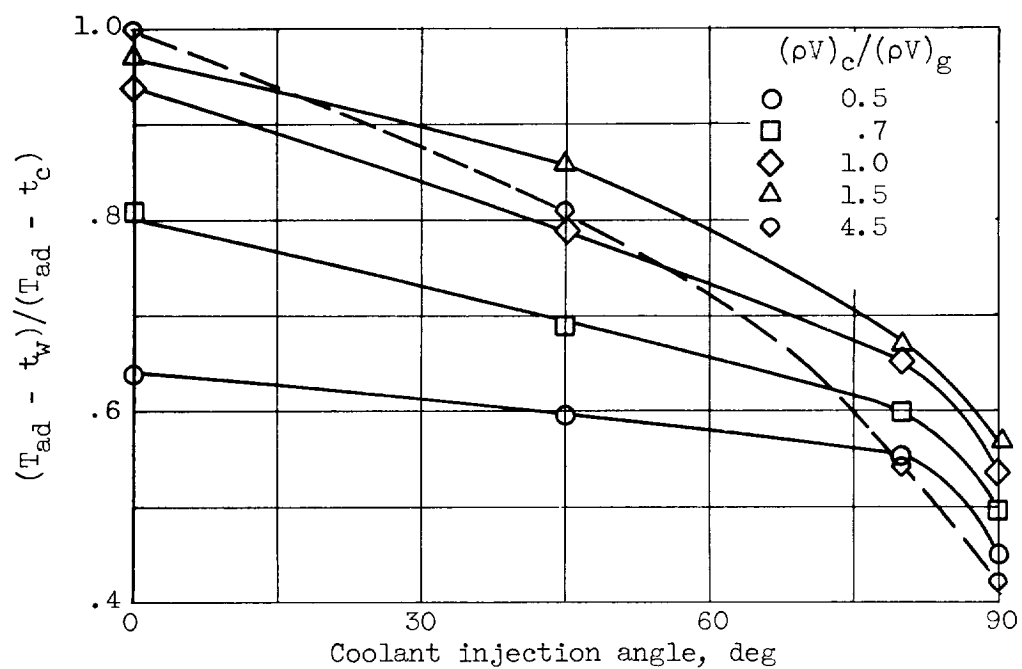


Figure 2. - Decreasing film-cooling effectiveness caused by increasing coolant injection angle for $S = 1/4$ inch; $T_{ad} = 1500^\circ \text{ R}$; $x = 6.51$ inch; t_c range, 530° to 1000° R ; $M_g = 0.5$.

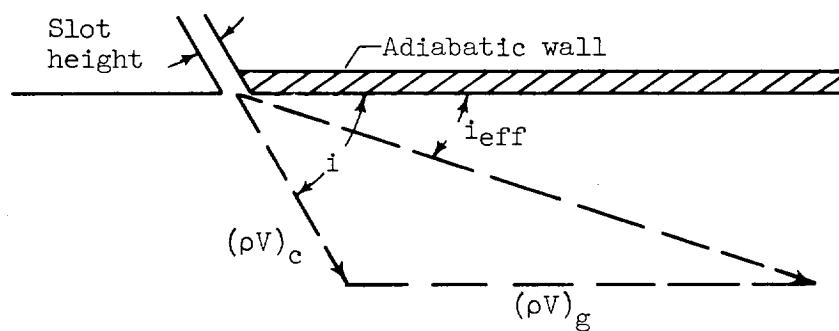


Figure 3. - Schematic representation of interaction of coolant and main gas streams.

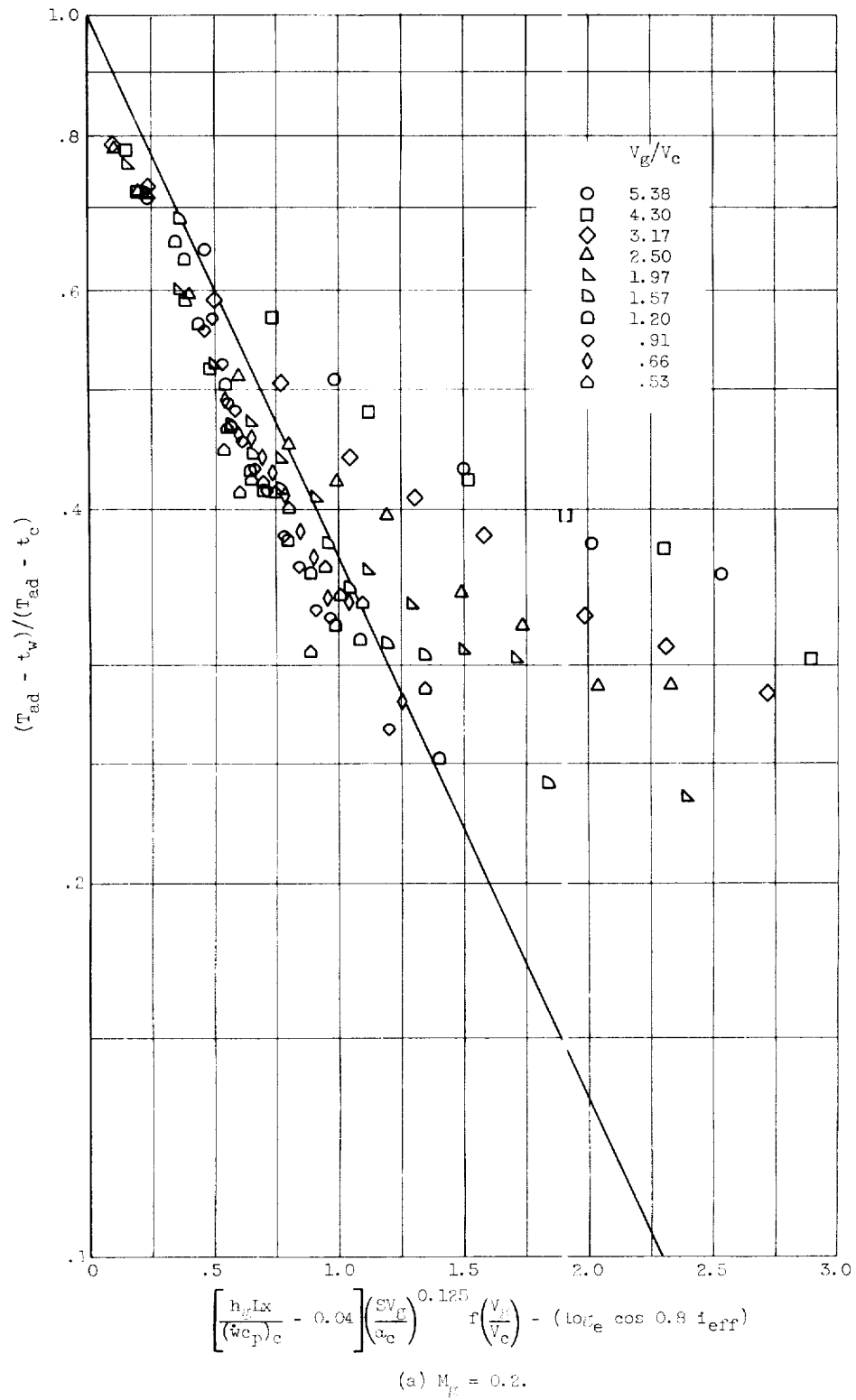


Figure 4. - Slot data correlation for coolant injection angle of 90° .
 $S = 1/4$ inch; $T_{ad} = 1500^\circ$ R.

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CB-3

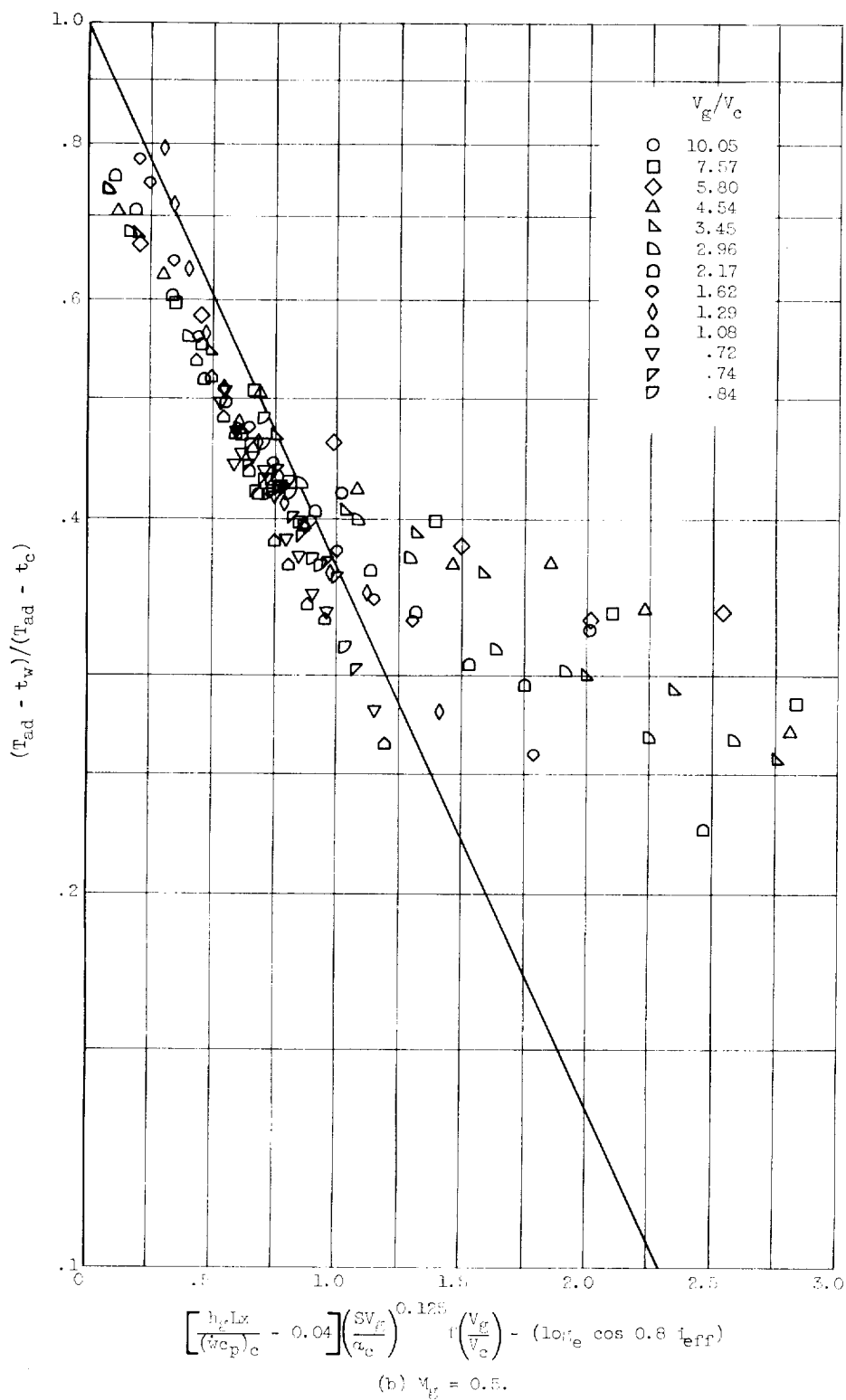


Figure 4. - Continued. Slot data correlation for coolant injection angle of 90° . $S = 1/4$ inch; $T_{ad} = 1500^\circ$ R.

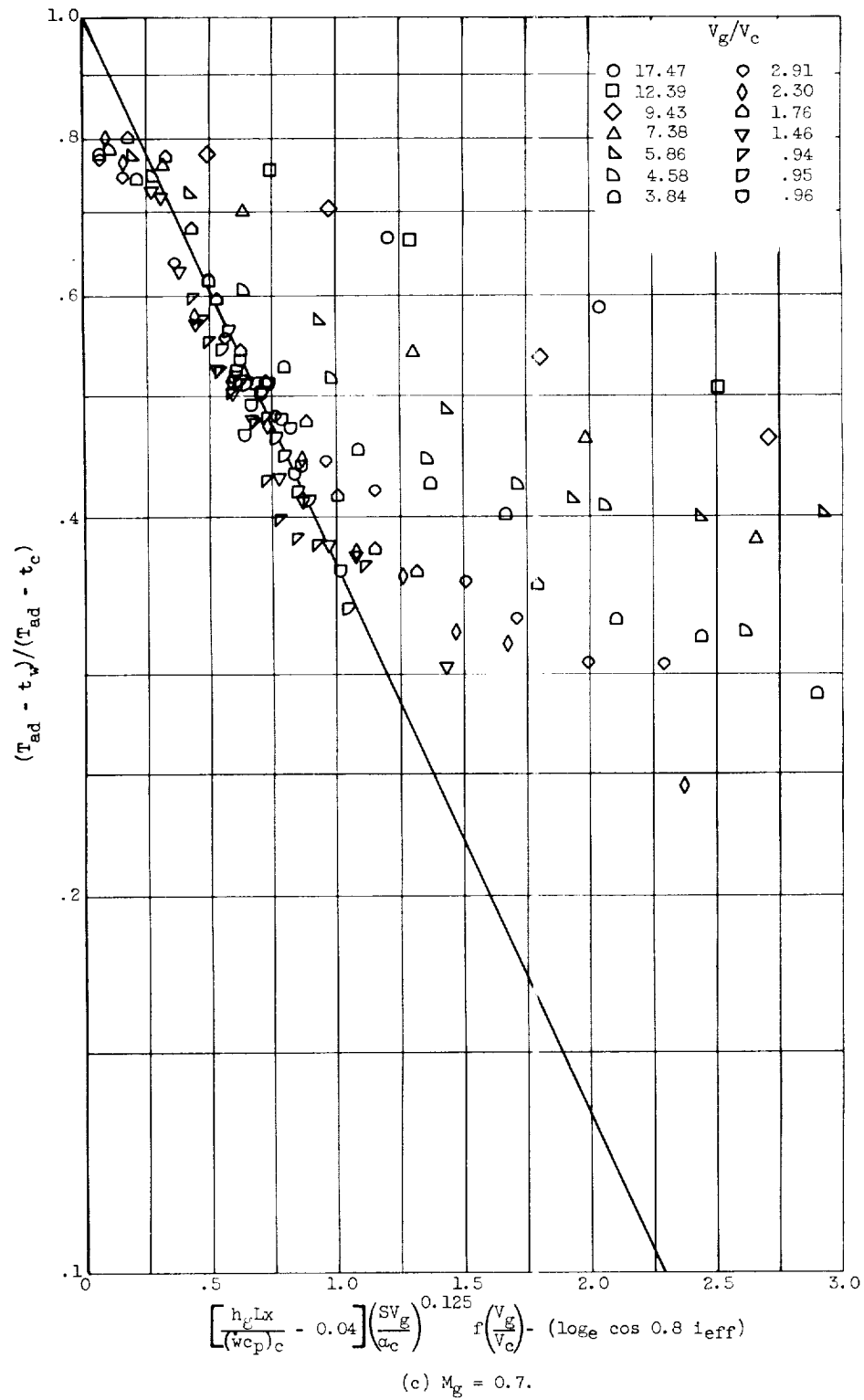


Figure 4. - Concluded. Slot data correlation for coolant injection angle of 90°. $S = 1/4$ inch; $T_{ad} = 1500^\circ R$.

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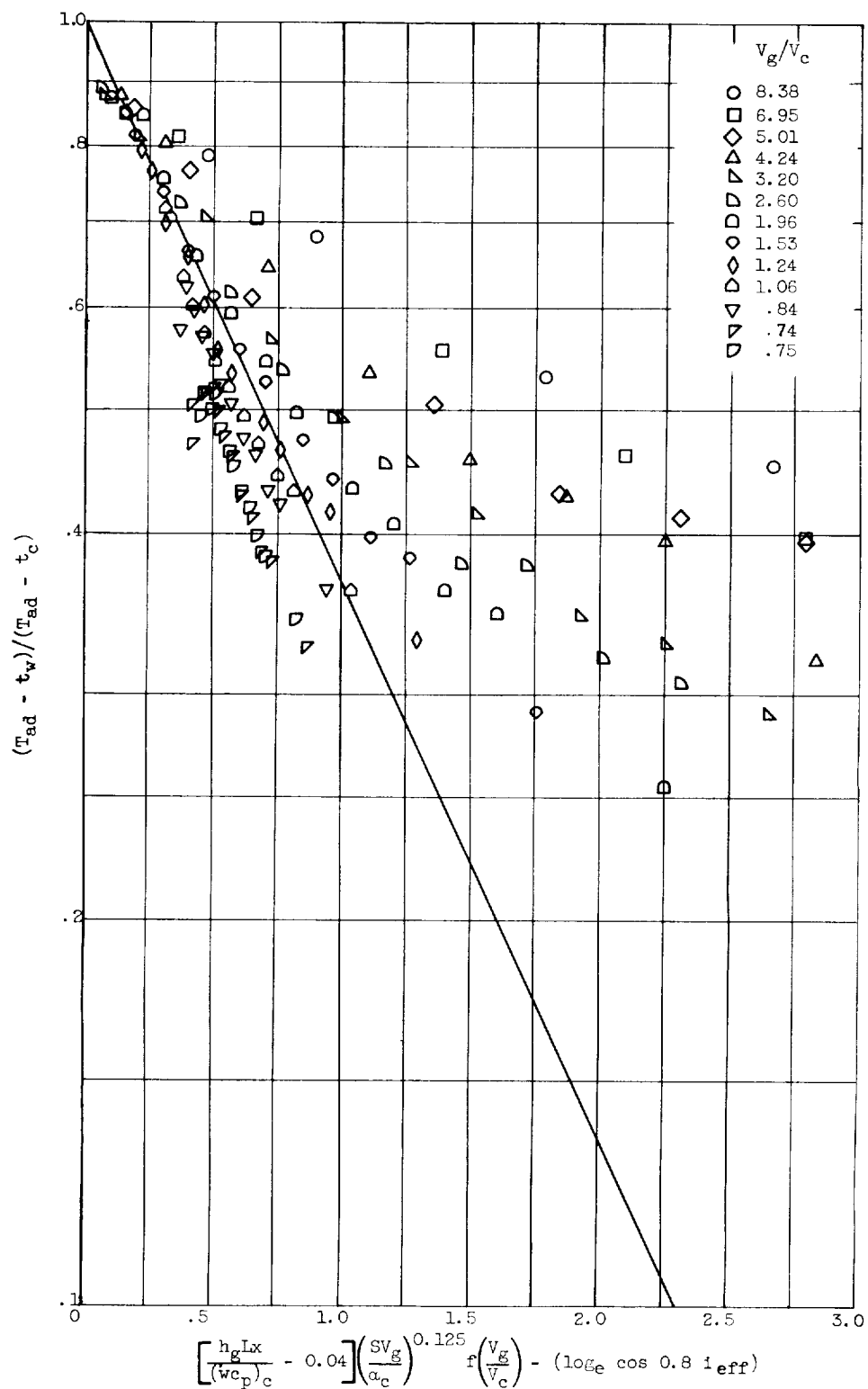


Figure 5. - Slot data correlation for coolant injection angle of 80° .
 $S = 1/4$ inch; $T_{ad} = 1500^\circ R$; $M_g = 0.5$.

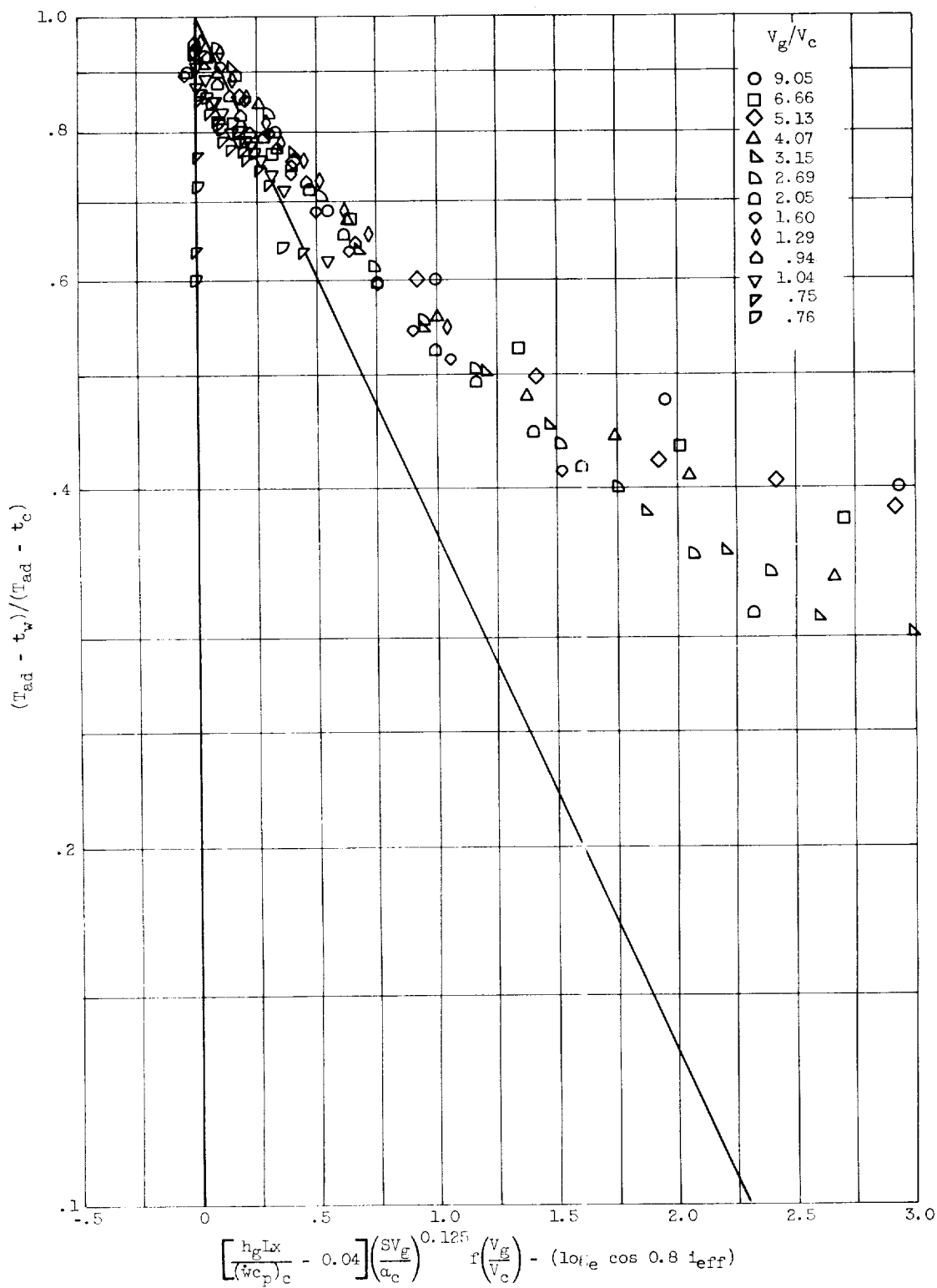


Figure 6. - Slot data correlation for coolant injection angle of 45° . $S = 1/4$ inch;
 $T_{ad} = 1500^\circ R$; $M_{te} = 0.5$.

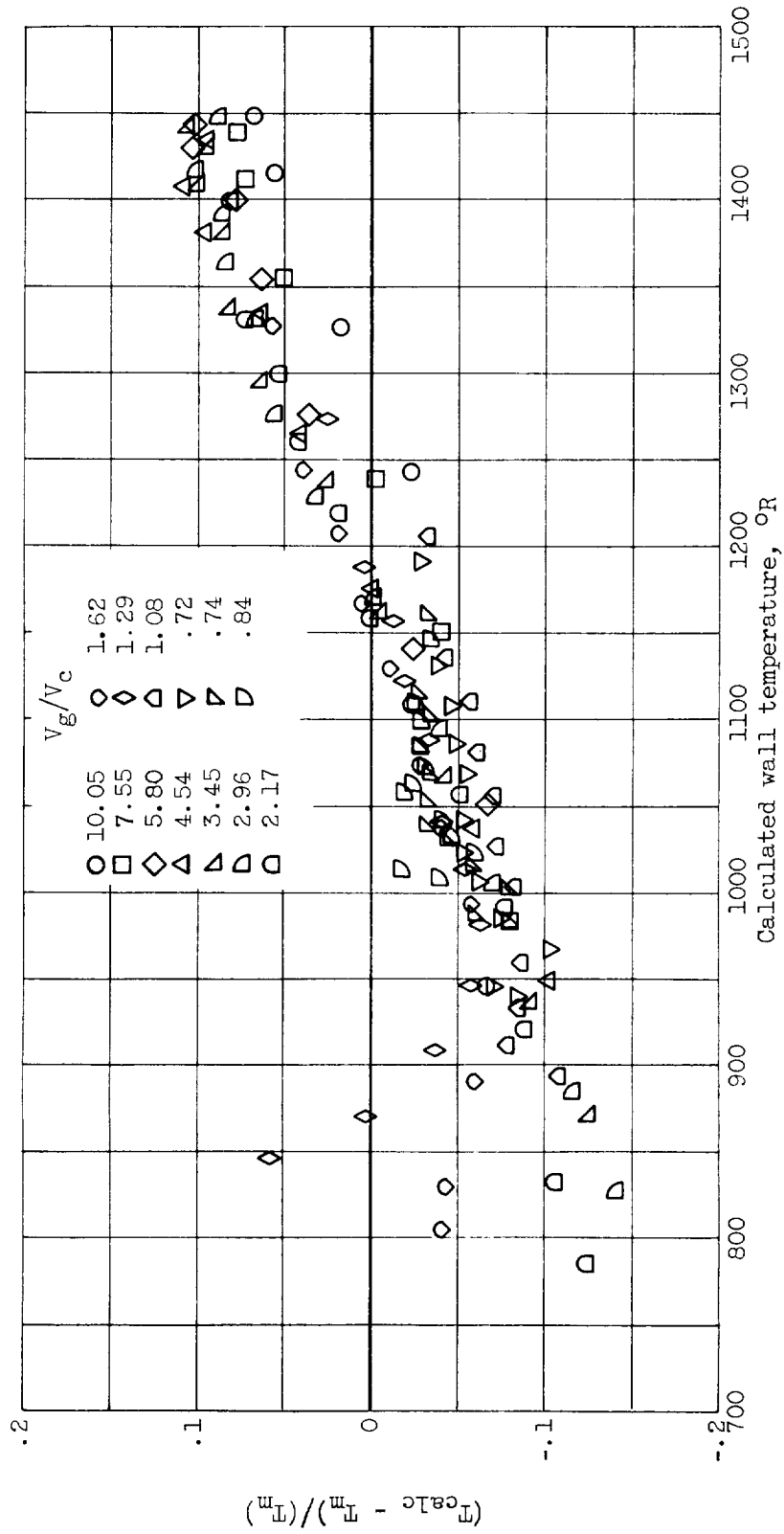


Figure 7. - Deviation of wall temperature calculated by equation (2) from measured wall temperature for data presented in figure 4(b).

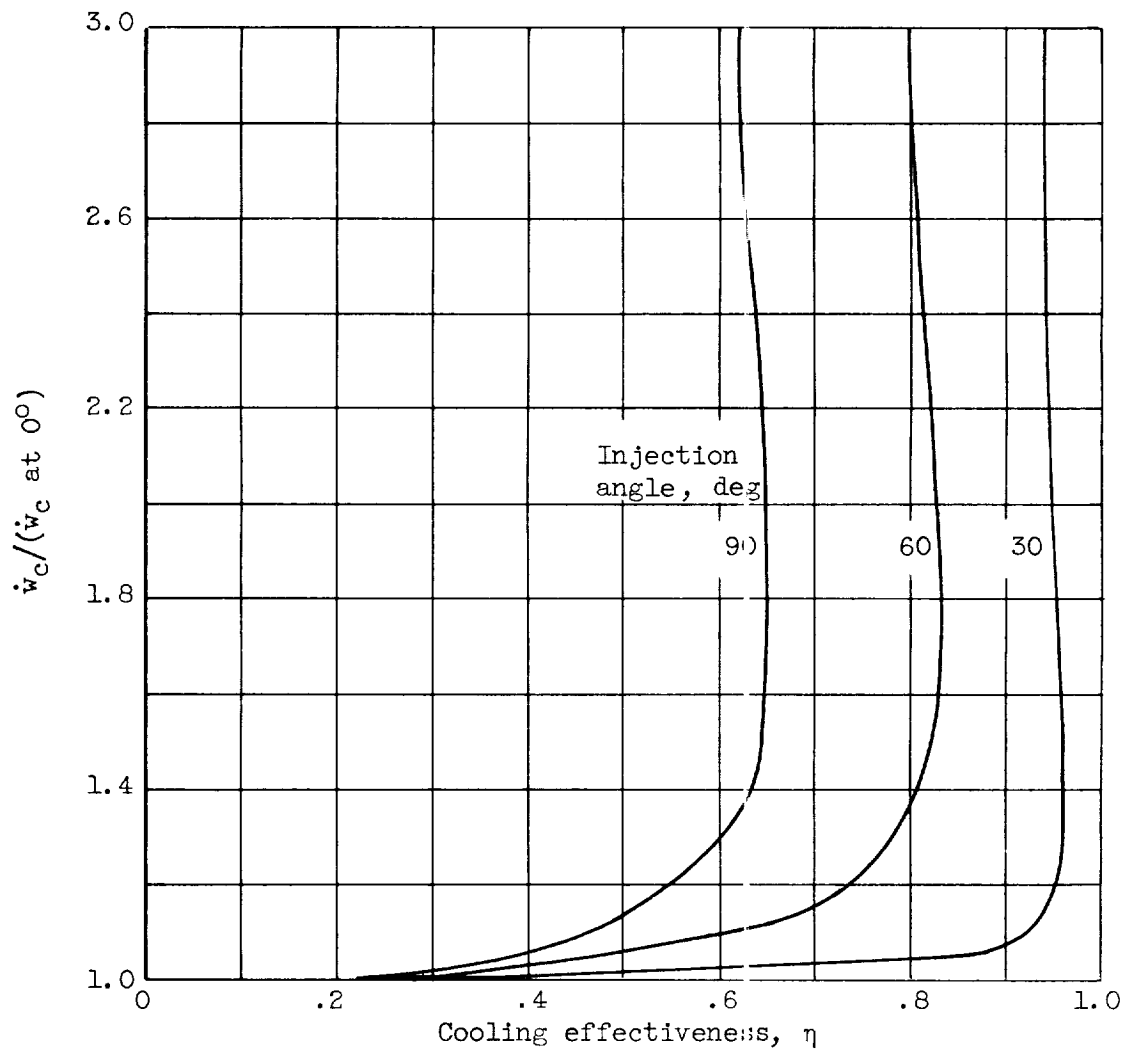


Figure 8. - Angle effect - coolant weight flow penalty calculated by use of equation (2) for $\dot{w}_g = 12.0$ pounds per second; $T_{ad} = 1470^\circ \text{ R}$; $t_c = 780^\circ \text{ R}$; $x = 6.5$ inches. Flow dimensions from figure 4(a) of table I(a).

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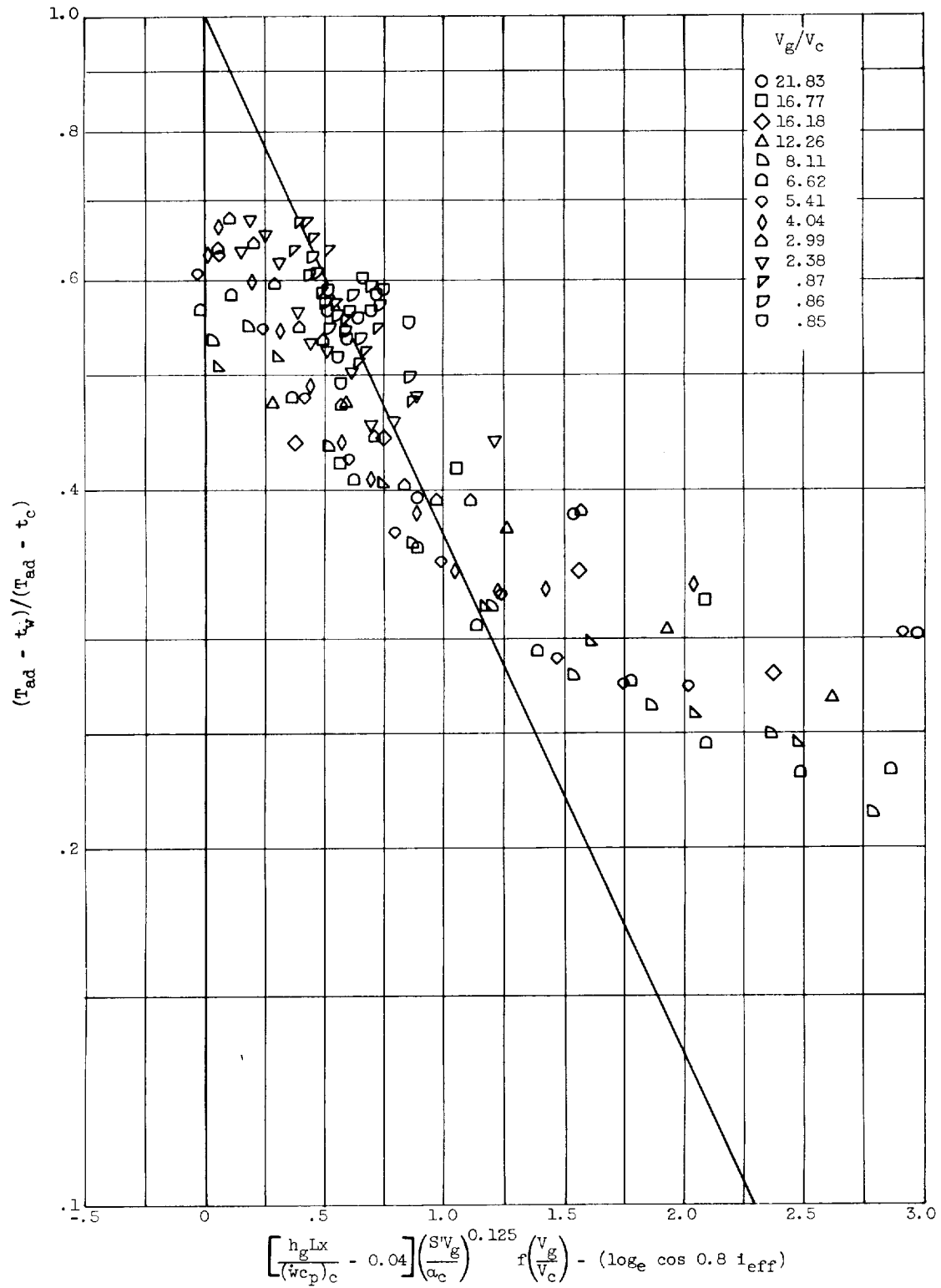


Figure 9. - Application of slot correlating equation to normal hole injection data.
 Configuration: four rows of 1/4-inch holes; $S' = 0.403$ inch; $T_{ad} = 1500^\circ \text{ R}$; $M_g = 0.7$.

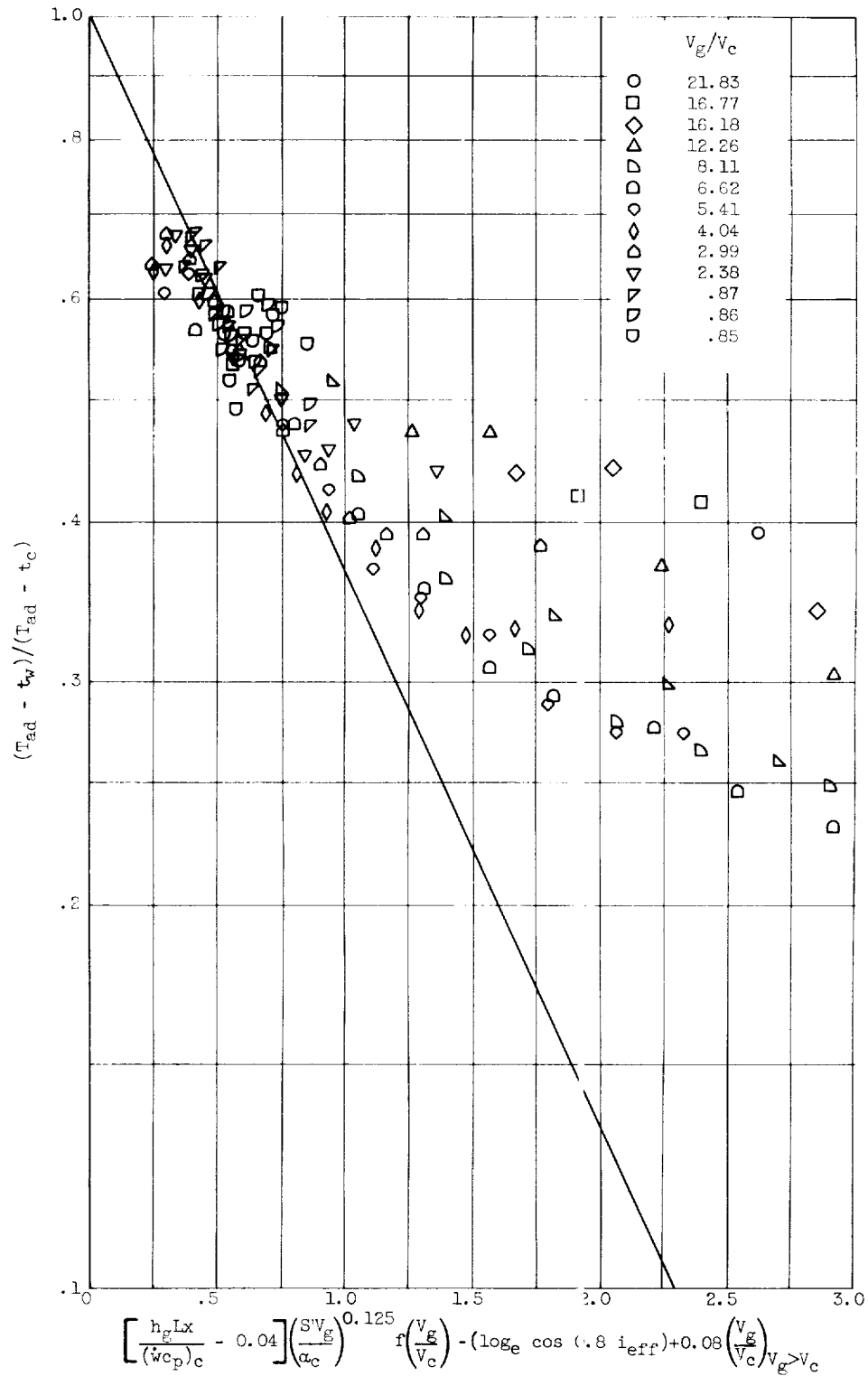


Figure 10. - Hole data correlation applying velocity ratio corrective term to data of figure 9. Configuration: four rows of 1/4-inch holes; $S' = 0.403$ inch; $T_{ad} = 1500^\circ R$; $M_g = 0.7$.

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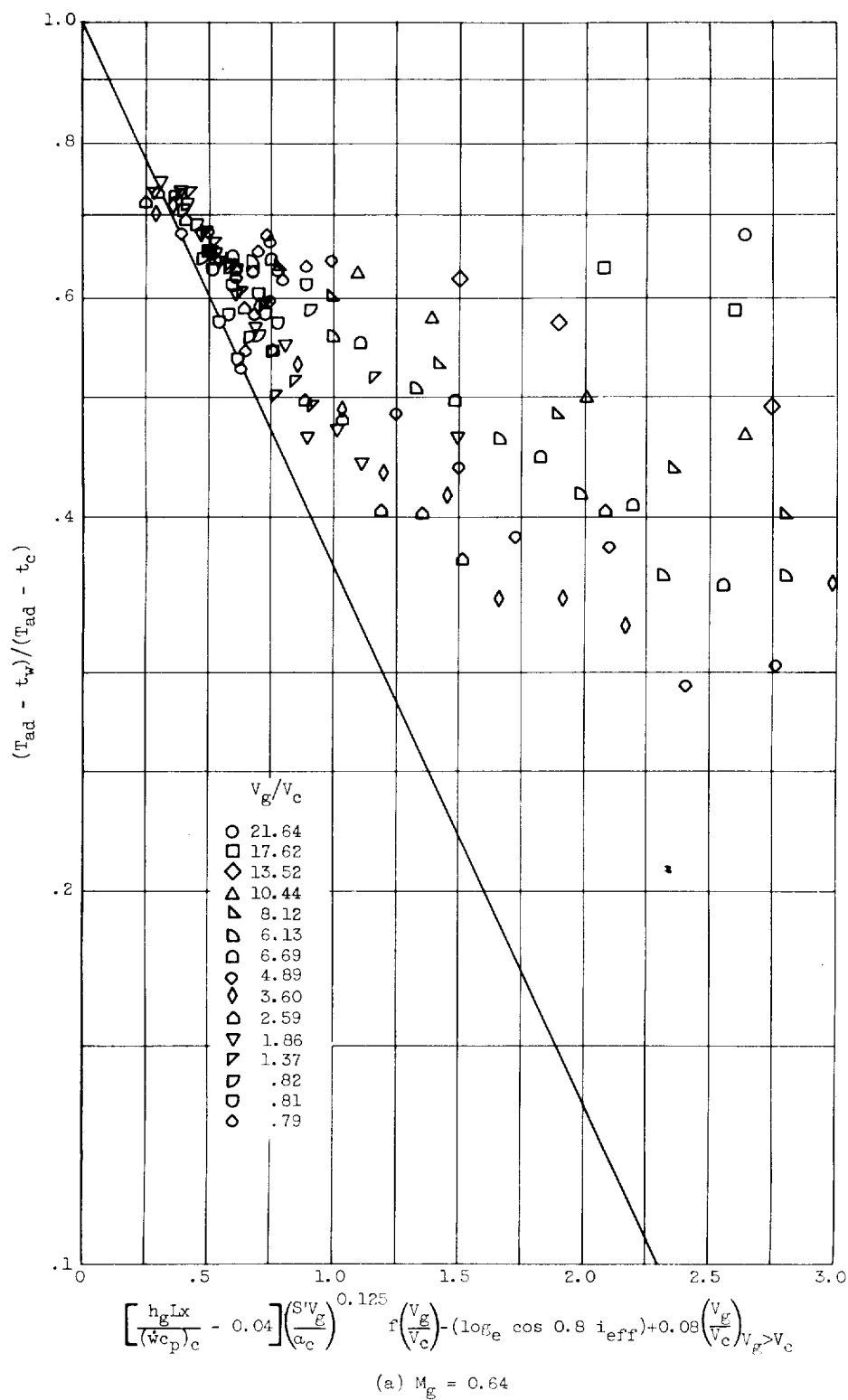


Figure 11. - Hole data correlation for a four-row configuration of 1/4-inch holes. $S' = 0.403$ inch; $T_{ad} = 1500^\circ \text{R}$.

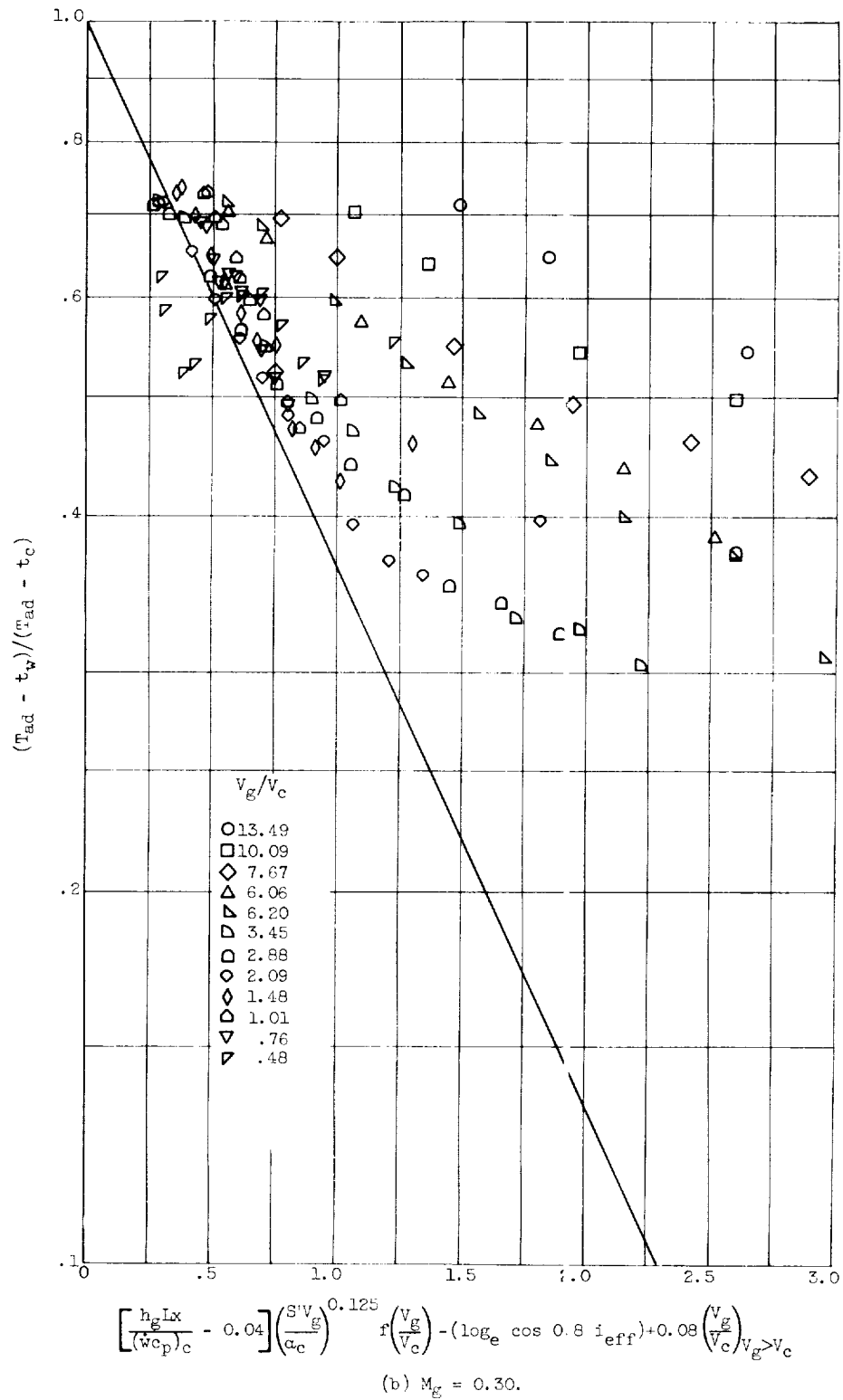


Figure 11. - Concluded. Hole data correlation for a four-row configuration of 1/4-inch holes. $S' = 0.403$ inch; $T_{ad} = 1500^\circ$ R.

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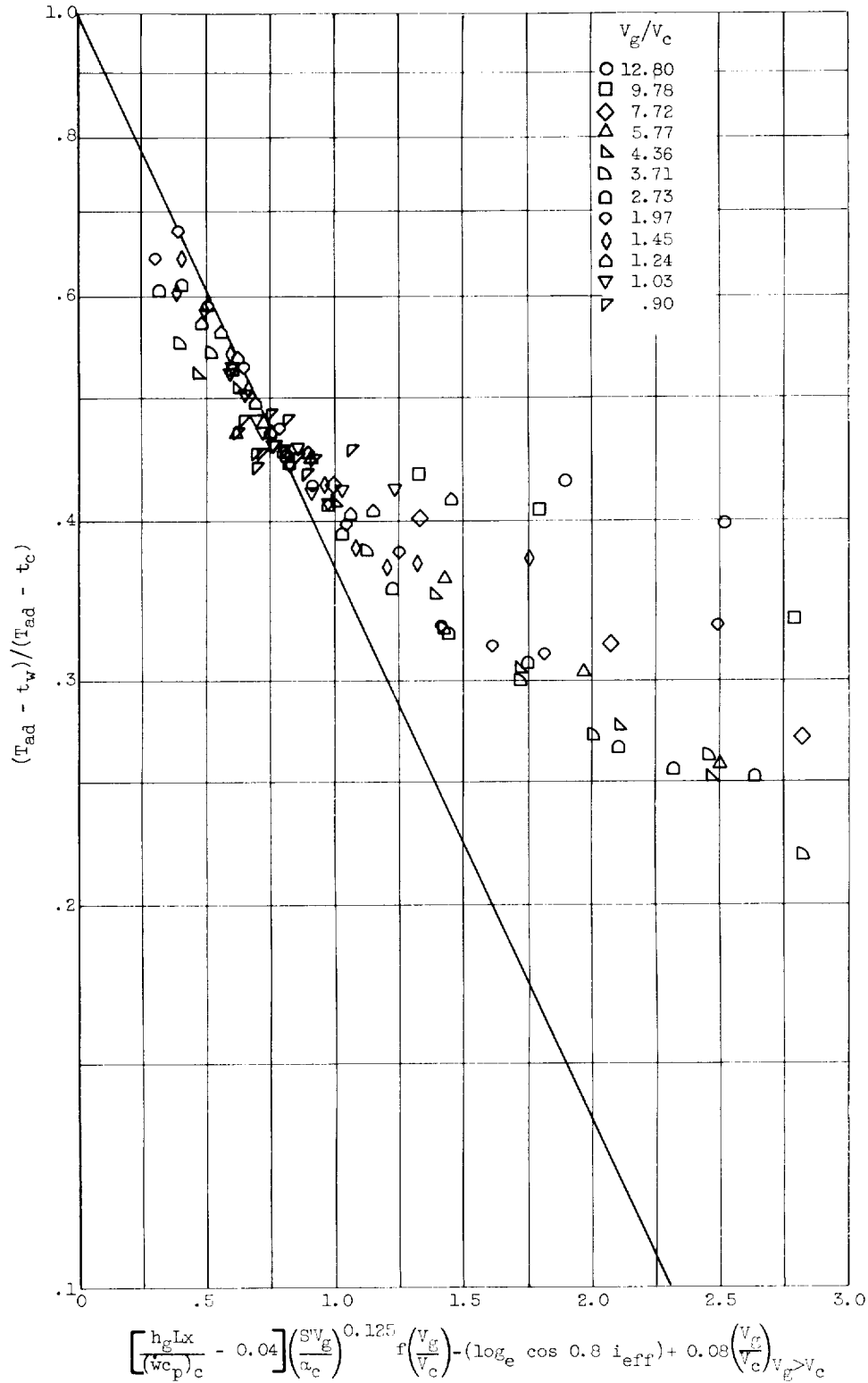


Figure 12. - Hole data correlation for a two-row configuration of 1/4-inch holes. $S' = 0.223$; $T_{ad} = 1500^\circ \text{R}$; $M_g = 0.69$.

